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LCA FOR AGRICULTURE

Consequential LCA of switching from maize silage-based to grass-based dairy systems

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Abstract
Purpose This study aimed to investigate the environmental consequences (on climate change and land use) of an increase in preference for grass-based milk in France using a consequential life cycle assessment (CLCA) approach. This increase in preference was assumed to be satisfied domestically, by converting maize silage-based dairy farms (MS farm) to grass-based dairy farms (G farm) while keeping on-farm usable agricultural area and total milk production of farm constant.
Methods The possible consequences of an increase in preference for grass-based milk were identified based on cause and effect relationships. The conversion from MS to G farm reduced the use of soybean meal, changed the on-farm cropping pattern and produced more animals but less wheat and no rapeseed. Effects on on-farm soil C were predicted with the RothC model and on global land use change (LUC) with models of global agricultural markets (Global Trade Analysis Project (GTAP) and Landbouw Economisch Instituut Trade Analysis Project (LEITAP)). System expansion using animals from a suckler beef production system was applied to estimate the impacts of milk and animal co-products from the dairy system. Land occupation and climate change impacts were estimated. The consequences of farm conversion were attributed only to the milk, as preference for grass-based milk drove the conversion process.
Results and discussion The conversion from the MS to G farm increases land occupation and climate change impacts for the G farm, respectively, by 9 and 7 % according to GTAP and 14 and 51 % according to LEITAP. Land occupation and climate change impacts of milk produced by the G farm after conversion increased, respectively, by 82 and 13 % with GTAP and 123 and 97 % with LEITAP relative to those for the MS farm (before conversion). The production of additional wheat and rapeseed outside the G farm increased impacts of the G farm (by 29–69 % depending on impacts and model used). Results indicate that the farm conversion would probably have consequences on global LUC and that it is important to account for this in a LCA approach.
Conclusions Land use and land use change (LULUC) contributed to the impacts of grass-based milk, and results were highly sensitive to the LULUC model used. The many possible chain-of-event pathways that follow a change in preference for a given product yield high uncertainty in CLCA results. This study only assessed one possible way to meet the increase in preference for grass-based milk; it is necessary to perform a sensitivity analysis to investigate other possible scenarios resulting from this increase in preference.

Keywords Climate change · Consequential LCA · Grass-based milk · Land occupation · LULUC · Maize silage-based milk

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1 Introduction

Worldwide, the dairy sector is estimated to contribute 4 % to the total global anthropogenic greenhouse gas (GHG)

emissions (FAO 2010). The dairy sector is estimated to contribute 20–30 % to the total GHG emissions of the European Union (EU) livestock production (Weiss and Leip 2012). In France, 50 % of milk production (representing 46 % of dairy farms) comes from production systems with a high percentage (>30 %) of silage maize in the total forage area; they are based mainly in western France (Institut de l'Elevage 2009). In contrast, grass-based milk production (i.e. <5 % of silage maize and >80 % of grassland in the total forage area) concerns only 8 % of milk production and 11 % of dairy farms, which are based mostly in mountainous or semi-mountainous areas (Institut de l'Elevage 2009). Grass-based milk production reduces feed cost and farm sensitivity to increased input prices and economic fluctuations (Institut de l'Elevage 2009). Compared to silage maize, grassland also increases C sequestration in soil (Soussana et al. 2010), reduces nitrate leaching (Vertès et al. 2012) and enhances macro-scale biodiversity of the production system (e.g. Robertson et al. 2012). Grass-based milk has higher nutritional quality than maize silage-based milk due to higher linolenic acid content in milk fat (Chilliard et al. 2001). Thus, grass-based dairy production systems appear to have several economic and environmental advantages, and development of these systems has been encouraged in France over the past decade (Alard et al. 2002; Peyraud et al. 2009).

The consequential life cycle assessment (CLCA) approach aims to describe how physical flows may change in response to possible changes in the life cycle of the product under study (Ekvall and Weidema 2004). CLCA studies applied to agriculture have most frequently concerned (oil) crops and biofuel production (Dalgaard et al. 2008; Schmidt 2008; Reinhard and Zah 2009). To our knowledge, the only study using CLCA modelling to analyse ruminant production systems is by Thomassen et al. (2008), who modelled consequences of meeting increased demand for milk with an additional dairy farm. In this study, affected processes (i.e. those expected to be affected most by the increased demand) included electricity produced by a natural gas power plant and marginal barley and soybean meal (i.e. marginal feed energy and protein supplies, respectively); as for co-product handling, system expansion was applied by assuming that meat from the additional dairy system would replace a mix of suckler beef and pork. Nevertheless, Thomassen et al. (2008) did not investigate how to meet the increased demand for area (in particular grassland area) required for milk production by an additional farm and its land use and land use change (LULUC) consequences. Thus, the goal of our study was to investigate the potential consequences on climate change and land use of an increase in preference for grass-based milk in France by using the CLCA approach and integrating the effects on land use change (LUC).

2 Methodology

2.1 CLCA approach

The consequences of an action can propagate through global economic and technological systems in chains of cause and effect relationships (Ekvall and Weidema 2004). Thus, CLCA represents a convergence of LCA and economic modelling methods (Earles and Halog 2011). The CLCA approach was used as a tool in this study to model different ways to satisfy an increased preference for grass-based milk in France. First, we assumed that an increasing number of French consumers would purchase grass-based (G) milk instead of "conventional" milk (i.e. maize silage-based (MS) milk). We then assumed that this change in preference would be met by increasing grass-based milk production by converting 50 % of maize silage-based milk production in France to grass-based milk production.

According to a framework proposed by Schmidt (2008) for increased crop demand in certain regions, this increased grass-based milk production would affect the systems producing other types of milk in France. We assumed that only production systems with a high percentage of silage maize (>30 %) in the forage area would be affected, because these systems lack the perceived economic and environmental advantages of the grass-based system and currently produce 50 % of French milk (Institut de l'Elevage 2009). Thus, we assumed that this increased preference would be met exclusively by modifying domestic production, that is, by converting a major fraction of French dairy farms using a feeding system largely based on silage maize (MS farm) to a feeding system mainly based on grass (G farm). As a G farm produces less milk per hectare than an MS farm (Pavie et al. 2010), the G farm requires more land to produce the same amount of milk.

Several ways to satisfy the increase in area of G farms were identified based on realistic cause–effect relations proposed by Smyth and Murphy (2011) (Fig. 1). We assumed that the additional area for G farms would come at the expense of area used for (dairy or beef) cattle production or crop production. All scenarios identified resulted in LUC at the end of the cause–effect chain, which begun by increased preference for grass-based milk. The consequences of LUC were estimated by integrating the results of Edwards et al. (2010), who predicted the effects of increased biofuel demand on LUC with several economic models. In this paper, we investigated only the scenario 1 (see Fig. 1) because models to predict the effects of increased demand for animal products on LUC are not available, while such models are available for increased crop demand (e.g. due to increased biofuel demand). Thus, this study presents an example exploring the environmental consequences of increased preference for grass-based milk in France.

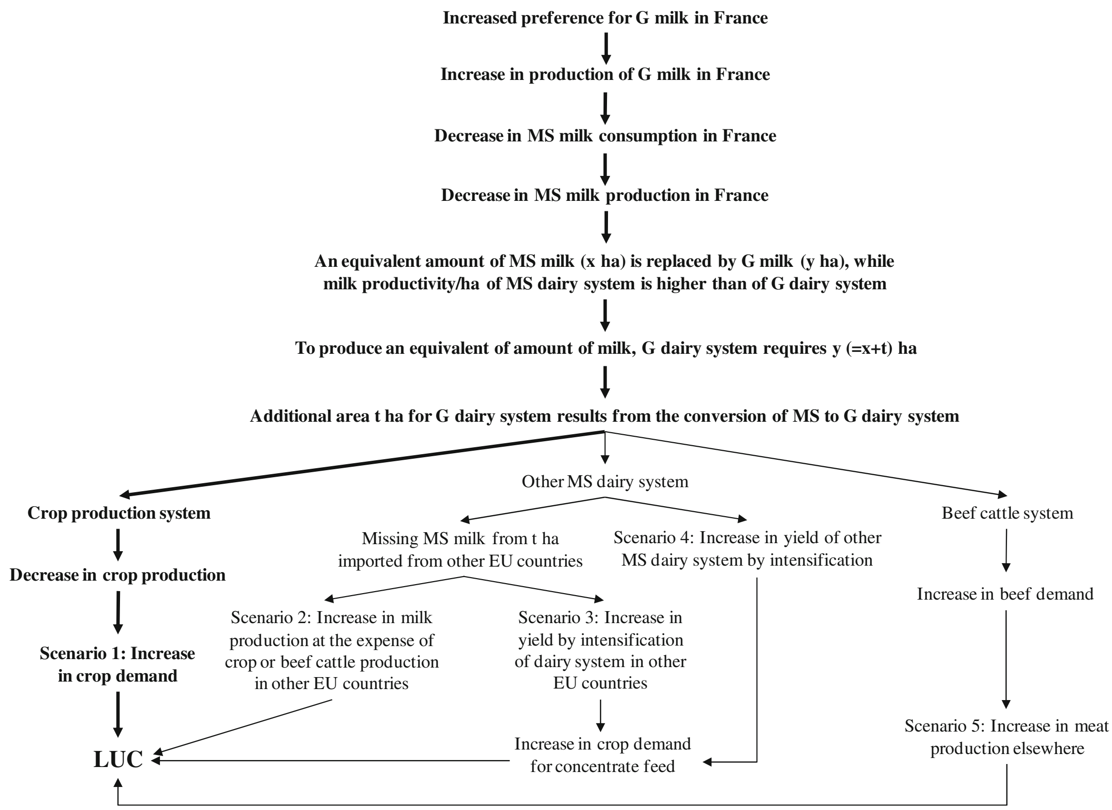

Fig. 1 Possible consequences of increased preference for grass-based milk in France, with the cause and effect chain explored in the study in *bold*

2.2 Description of dairy farms

Data for the MS and G farms were as in Nguyen et al. (2013), based on a typical dairy production system in Normandy (northwestern France) (Pavie et al. 2010) and on experimental results (Delaby et al. 2009). These sources provided reliable and detailed data at the farm level for dairy production systems. The MS and G farms correspond to the G/HM-Ho (high silage maize percentage in the total forage area and Holstein breed) and G-Ho (grass only in the total forage area and Holstein breed) dairy farms described in Nguyen et al. (2013), respectively. As a G farm requires more land than an MS farm to produce the same amount of milk (Delaby and Pavie 2008), we configured both farms to have the same usable agricultural area (UAA) and milk production but they differ in the percentage of area devoted to forage and cash crop production. We assumed that the MS farm (as described below) would be representative of production systems in France with a high percentage (>30 %) of silage maize in the total forage area. The G farm was representative of intensive grass-based production systems in France, i.e. systems that use relatively high amounts of N fertiliser on grassland to maximise yield and thus milk production per hectare.

2.2.1 Maize silage-based dairy farm

The MS farm occupies 55 ha of UAA, including a dairy production subsystem (28.7 ha) with a quota of 250,000 l of milk and a cash crop subsystem (26.3 ha). The cash crop subsystem produces wheat (17.8 ha) and rapeseed (8.5 ha). The MS dairy subsystem has highly productive Holstein cows (8.66 t fat- and protein-corrected milk (FPCM)/cow/year) and 33 % of its forage area is occupied by silage maize. The herd consists of 32 cows (11 primiparous) that annually provide 29 calves, 13 of which are kept to be raised as heifers to replace cull cows. During the indoor period (September to mid-March), cows are fed mainly with maize silage and concentrate feed. During the grazing period (120 days, including transition), cows mainly graze but are supplemented with maize silage and concentrate feed. Cows have their first calving at 25 months, and all calving is grouped at the end of summer. During drying off, cows graze and are supplemented with maize silage and concentrate feed.

2.2.2 Grass-based dairy farm

The G farm results from a conversion from the MS farm on the same 55 ha of UAA (Fig. 2). The number of cows has increased, as cows in the G farm yield less milk per year (6.74 t FPCM) than those in the MS farm. Thus, the herd consists of 41 cows (17 primiparous) that annually provide 38 calves, 19 of which are raised as heifers to replace cull cows. During the indoor period (mid-December to March), cows are fed mainly with conserved grass and concentrate feed. During the grazing period (205 days, including transition), cows mainly graze and are supplemented with grass silage and minerals. Cows have their first calving at 36-months, as heifers have a low growth rate due to their grass-based diets, and all calving is grouped at the end of autumn. Drying off occurs during the indoor period, with cows fed with grass silage. The total forage area for this herd is 47.6 ha, leaving 7.4 ha for wheat in the cash crop subsystem.

In each dairy subsystem, we assumed that 8 % of the milk produced is not sold because it is fed to calves or lost due to diseases such as mastitis. Calves not kept for replacement are sold after 2 weeks (55 kg live weight). We assumed that one heifer died at the end of the first year. Heifers are raised up to their first calving, but those not incorporated into the cow herd are sold as pregnant heifers. We assumed that one cull cow died; the rest are fattened with grass silage and concentrate for 2 months before slaughter. We assumed that losses during grazing or conservation and feeding of grass are about 15 % of the dry matter (DM) produced, and losses during conservation and feeding of maize silage are about 10 % of the DM produced. Cows are raised indoors in a loose housing system, and slurry from the feeding area is evacuated and stored outside the animal housing. The bedding area for lactating cows is covered with straw, and solid manure is collected indoors and removed every 2 months. Other types of animals are housed in deep bedding, and manure is

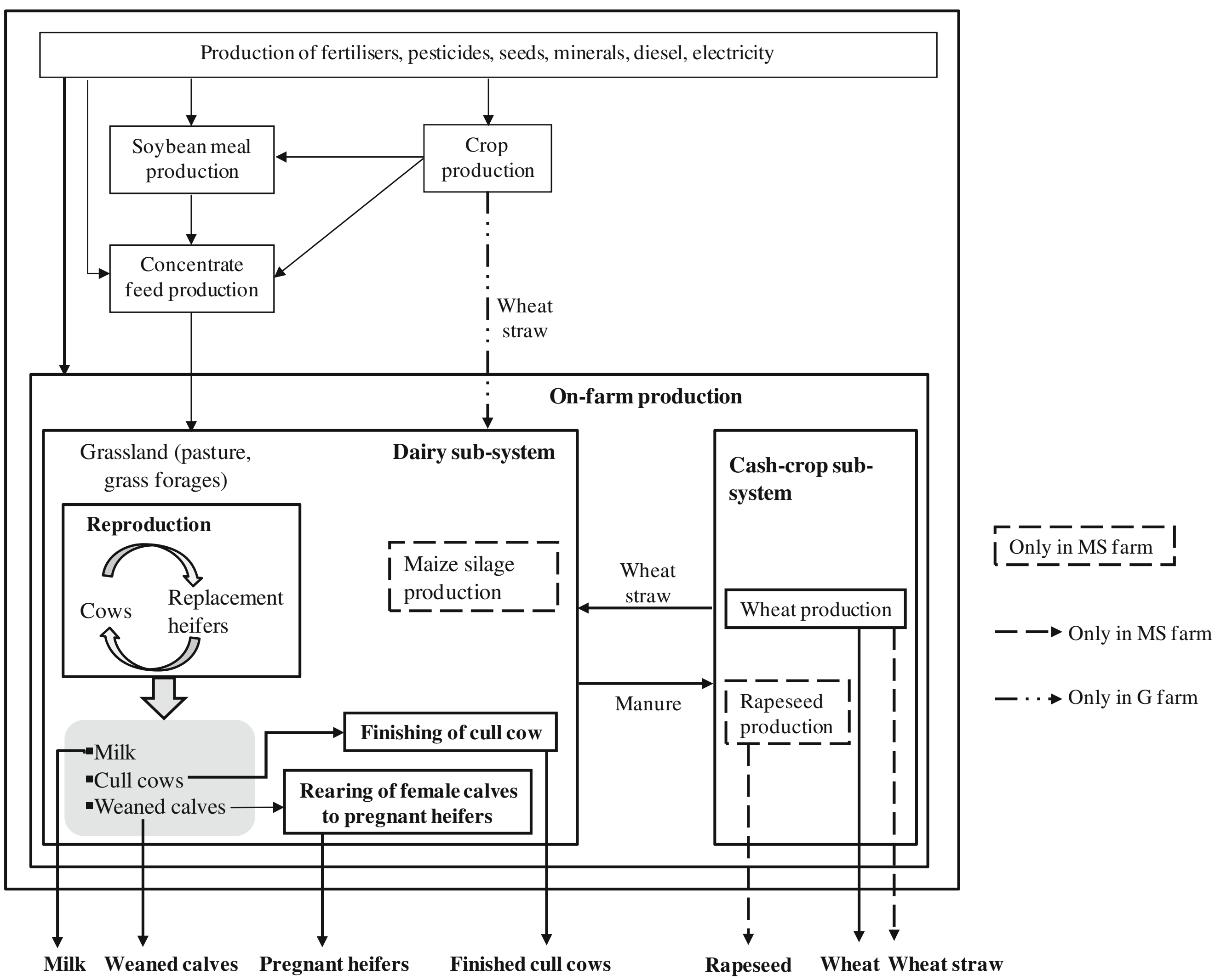

Fig. 2 Diagram of material flows of the dairy farm with a high percentage of silage maize in the total forage area (MS farm) and the one based exclusively on grass (G farm)

collected indoors and removed once per year. Table 1 and Fig. 2 describe the material flows for inputs used and product outputs of two dairy farms; further details are presented in Nguyen et al. (2013).

2.3 System boundary

The increased preference for grass-based milk in France induced the conversion of MS farms to G farms, resulting in consequences both in the French region where farm conversion occurred, due to changes in land use and farm management, as well as in the rest of France and the world, due to changes in feed provision and product outputs (crops, milk and animals). Therefore, the system boundary of this scenario includes the dairy farm (i.e. inputs used for grassland, feed, herd management and associated upstream processes, emissions from animals, manure storage and application to grassland), the effect on soil C stock due to changes in on-farm land use and management and the effects due to changes in inputs (e.g. less soybean meal used) and outputs (e.g. fewer crops and more meat produced) of the dairy farm to the global market (Fig. 3). The functional unit was 1 t of FPCM leaving the farm gate.

2.4 Consequences of farm conversion

To explore the consequences of increased preference for grass-based milk, we modelled the consequences from the conversion of an MS farm to a G farm, as described below.

2.4.1 Change in herd structure and meat production

When the conversion from MS to G occurs, nine cows and six heifers must be added to the herd to maintain the same milk production. We assumed that these animals were purchased at conversion. For the sake of simplicity, we did not consider impacts associated with these animals, as this purchase only occurs once (at the transition) and this additional stock will be available once the farm is sold or ended. We thus assumed a zero-sum situation. The G herd also produces three more calves and six more cull cows per year than the MS herd, which we

Table 1 Characteristics of the maize silage-based dairy farm (before farm conversion) and grass-based dairy farm (after conversion)

	Unit	Maize silage-based	Grass-based
On-farm area	ha	55.0	55.0
Temporary grassland	ha	9.3	23.1
Permanent grassland	ha	10.0	24.5
Silage maize	ha	9.4	0.0
Wheat	ha	17.8	7.4
Rapeseed	ha	8.5	0.0
Herd characteristics			
Cows	Animals	32	41
Heifers (0–1 year)	Animals	13	19
Heifers (1–2 years)	Animals	12	18
Heifers (2–3 years)	Animals	0	18
Replacement rate	%	34	41
Cull rate	%	31	39
FPCM	t/cow/year	8.66	6.74
Concentrate feed-fed			
Wheat	t dry matter	11.4	13.2
Soybean meal	t dry matter	29.1	8.8
Minerals	t dry matter	3.9	4.4
Dairy farm outputs (sold)			
FPCM	t	254.9	254.2
Finished cull cows	t live weight	7.4	11.8
Weaned calves	t live weight	0.9	1.1
Pregnant heifers	Animals	1	1
Wheat	t dry matter	113.5	47.2
Rapeseed	t dry matter	27.4	0.0

FPCM fat- and protein-corrected milk

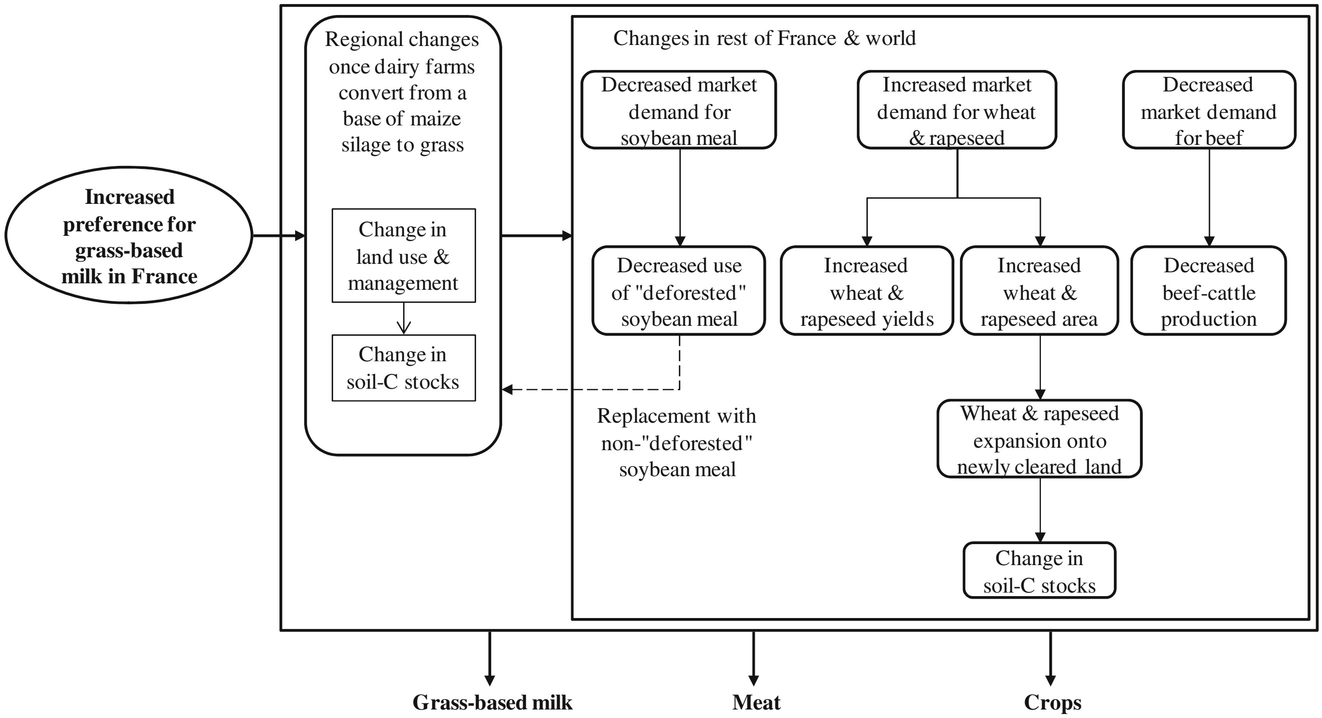

Fig. 3 System boundary of increased preference of grass-based milk in France

assumed to decrease demand, and therefore production, of suckler beef cattle. Avoided impacts of suckler beef cattle production were taken from Nguyen et al. (2012).

2.4.2 Change in on-farm cropping pattern and rotation and their influence on C stock of farm soil

To satisfy forage requirements for the G herd, on-farm cropping pattern and its associated rotation change (Table 2), we assumed that all temporary grassland, i.e. grassland less than 5 years old, and some of the silage maize area on the MS farm are converted to permanent grassland, i.e. grassland older than 30 years, on the G farm, while the rest of the silage maize area, the entire rapeseed area and some of the wheat area are converted to temporary grassland. Thirty years of C dynamics in the topsoil (0–30 cm) was simulated for each rotation of each farm with the model RothC 26.3 (Coleman and Jenkinson 1996). RothC has been used and tested extensively under various climates and agricultural contexts, including grasslands (Smith et al. 1997). Input variables of RothC include initial C stock; monthly rainfall, temperature and evapotranspiration; amount of plant cover; soil clay content; and organic C inputs (e.g. plant residues, organic fertilisers). These variables were estimated for MS and G farms in Normandy, France. Table 2 shows predicted changes in soil C stock due to conversion-induced changes in cropping patterns.

2.4.3 Consequences of decreased on-farm cash crop production

As most of the cash crop area is converted to grassland, less wheat and rapeseed are provided to the international market, which increases their prices; this lowers demand for them and encourages increased production (Kløverpris et al. 2010). Production of a crop can increase in three ways: increasing yields in existing fields via intensification, replacing other crops with the desired crop (crop displacement) and expanding production onto other land use types (e.g. forest, grassland), which causes LUC (Edwards et al. 2010; Kløverpris et al. 2010). In reality, many causal chains of crop displacement will occur simultaneously in response to a changing supply of or demand for crops; to assess them, a simulation model of world agricultural markets is essential (Edwards et al. 2010). We therefore used results of Edwards et al. (2010), who predicted the effects of increased biofuel demand on LUC with several economic models. Using such models requires the strong assumption that changes in international markets respond linearly to the magnitude of crop demand.

To analyse the sensitivity of LUC predictions to models and their parameters, we used results from the Global Trade Analysis Project (GTAP, version GTAP-BIO) and the Landbouw Economisch Instituut Trade Analysis Project

Table 2 Change in cropping pattern and rotation due to the conversion from maize silage-based dairy farm (MS farm) to grass-based dairy farm (G farm) and consequences on average annual C stock increase of on-farm area simulated with RothC over a 30-year period

Cropping pattern of MS farm	Rotation of MS farm		Cropping pattern of G farm	Rotation of G farm	Increase in C stock due to farm conversion (t C/ha/year)	Area (ha)
Permanent grassland	PG	→	Permanent grassland	PG	0.29	9.3
Temporary grassland	TG5/M1/W1	→	Permanent grassland	PG	0.46	10.0
Silage maize	TG5/M1/W1	→	Permanent grassland	PG	0.46	2.0
Silage maize	M1/W1	→	Permanent grassland	PG	0.88	1.8
Silage maize	M1/W1	→	Temporary grassland	TG5/W2	0.48	5.6
Wheat	TG5/M1/W1	→	Temporary grassland	TG5/W2	0.06	2.0
Wheat	M1/W1	→	Wheat	TG5/W2	0.48	7.4
Wheat	R1/W1	→	Temporary grassland	TG5/W2	0.35	8.4
Rapeseed	R1/W1	→	Temporary grassland	TG5/W2	0.35	3.8
Rapeseed	R1/W1	→	Temporary grassland	TG5/TG5	0.35	1.2
Rapeseed	R1/W1	→	Temporary grassland	TG1/TG1	0.11	3.5

The number after the type of crop or grass indicates its duration (in years) in the rotation

PG permanent grassland, i.e. grassland older than 30 years, *TG* temporary grassland, i.e. grassland less than 5 years old, *M* silage maize, *W* wheat, *R* rapeseed

(LEITAP, version LEITAP2) models (Edwards et al. 2010). GTAP is a multi-region, multi-sector general equilibrium model based on neoclassical economic theory, in which prices adjust to create an equilibrium between supply and demand of all goods, services and production factors in the economy (Kløverpris et al. 2010). The version GTAP-BIO was designed specifically to analyse global impacts of expanded biofuel production (Edwards et al. 2010). The modified database used in GTAP-BIO was based on version 6 of the GTAP database, which represents the global economy with 87 regions and 57 sectors each, addresses biofuel by-products better and estimates global land use more accurately (Edwards et al. 2010). The LEITAP model, based on GTAP, was developed to analyse impacts of the EU biofuel directive on agricultural markets. The version LEITAP2 adds a land supply curve based on biophysical model outcomes from IMAGE (Eickhout et al. 2007) and Dyna-CLUE (Verburg et al. 2008) to predict LUC and distinguishes between marginal and average land productivity (Edwards et al. 2010).

Both models account for LUC area due to changes in by-products of biofuel production, food consumption and crop yields. Edwards et al. (2010) reported results as LUC area per tonne of oil equivalent (toe) of biofuel and the contribution of each of the three factors. In our study, the decrease in supply of crop products of the G farm relative to the MS farm results from the conversion of cropland to grassland; hence, no crop is produced on this land and no by-products are produced. Therefore, we did not consider the effect of by-products on the reduction in LUC.

From Edwards et al. (2010), we used results from the GTAP scenarios "Marginal extra ethanol from wheat demand in EU" (EU wheat ethanol) and "Marginal extra biodiesel from oilseed demand in EU" and the LEITAP scenarios "Increase in demand of ethanol from wheat in France" and "Increase in demand of biodiesel in Germany". In both GTAP and LEITAP scenarios, LUC due to increased biodiesel demand results from the production of the oilseed mix used to produce biodiesel. For our study, we assumed that LUC in biodiesel scenarios was caused only by rapeseed production. Table 3 presents LUC predictions from GTAP and LEITAP (Edwards et al. 2010) and the results used in our study (ignoring the use of by-products).

For example, the GTAP scenario "EU wheat ethanol" predicted that production of one additional toe ethanol requires additional 5.2 t of wheat as feedstock (see Table 3). However, wheat requirements decrease to 3.6 t due to the use of by-products from ethanol production (32 %) and then decrease further to 1.9 t due to a reduction in human consumption (46 %). Assuming a yield of 5.5 t/ha, producing this amount of wheat requires an area of 0.34 ha, from which an estimated 0.03 ha can be subtracted by increasing wheat yields. Then, the remaining 0.31 ha area can be partially "saved" by crop displacement. In this case, crop displacement resulted in an increase in demand for additional land by 0.48 ha. Thus, the net additional area needed is (0.31+0.48 =) 0.79 ha worldwide, which will come from forest and grassland. In fact, producing additional 0.79 ha of wheat requires producing 1.11 ha of wheat, 0.01 ha of oilseeds, 0.04 ha of other crops and stopping production of rice and coarse grain (i.e. cereal grains other than wheat and rice, used primarily for animal feed or brewing) on 0.36 ha (Table 4). Similarly, according to GTAP, without considering by-products, marginal demand for 1 t of wheat requires a net amount of 0.54 t of

Table 3 Land use change (LUC) key model parameters for GTAP and LEITAP models (Edwards et al. 2010) and their application in the present study for increases in demand of wheat and rapeseed due to farm conversion

Model/scenario used and application in this study	Gross demand of feedstock (t)	Reduction factor by using by-products (%)	Food consumption reduction factor (%)	Net demand of feedstock (t)	Average yield (t/ha)	Area without yield savings (ha)	Area "saved" by yield increase (ha)	Area "saved" by crop displacement (ha)	LUC (ha)
GTAP									
EU wheat ethanol[a]	5.2	– 32	– 46	= 1.92	÷ 5.5	= 0.34	– 0.03	– −0.48	= 0.79
EU biodiesel (mix)[b]	2.4	– 52	– 1	= 1.14	÷ 5.5	= 0.21	– 0.25	– −0.42	= 0.38
GTAP applied in this study									
Demand for wheat	1.0	– 0	– 46	= 0.54	÷ 5.5	= 0.10	– 0.01	– −0.14	= 0.22
Demand for rapeseed	1.0	– 0	– 1	= 0.99	÷ 5.5	= 0.18	– 0.22	– −0.36	= 0.33
LEITAP									
Wheat ethanol Fra[c]	5.5	– 1	– 3	= 5.28	÷ 4.2	= 1.26	– 0.15	– 0.38	= 0.73
Biodiesel Deu[d]	3.0	– 1	– 9	= 2.70	÷ 4.2	= 0.64	– 0.36	– −1.64	= 1.93
LEITAP applied in this study									
Demand for wheat	1.0	– 0	– 3	= 0.97	÷ 4.2	= 0.23	– 0.03	– 0.07	= 0.13
Demand for rapeseed	1.0	– 0	– 9	= 0.91	÷ 4.2	= 0.22	– 0.12	– −0.55	= 0.65

[a] Marginal extra ethanol from wheat demand in EU

[b] Marginal extra biodiesel from oilseed demand in EU

[c] Increase in demand of ethanol from wheat in France

[d] Increase in demand of biodiesel in Germany

wheat to be produced, resulting in 0.22 ha of LUC. In the same way, marginal demand for 1 t of rapeseed requires the production of a net amount of 0.99 t of rapeseed, resulting in 0.33 ha of LUC. For LEITAP, without considering by-products, marginal demand for 1 t of wheat requires a net production of 0.97 t of wheat, resulting in 0.13 ha of LUC. Similarly, marginal demand for 1 t of rapeseed requires a net amount of 0.91 t of rapeseed, resulting in 0.65 ha of LUC.

Average worldwide climate change impact data (not including LUC) associated with the production of principal crops (wheat, rice, maize, barley, sugar crops, rapeseed and soybean) were taken from Nemecek et al. (2011) (see Table 4). We assumed that coarse grain consisted of a 5:1 ratio of maize and barley and that sugar crops consisted of a 6:1 ratio of sugarcane and sugar beet based on worldwide production from 2003 to 2007 (FAOSTAT 2012). We assumed that oilseeds consist mainly of soybean (EU wheat ethanol/GTAP) or of a mix of soybean and rapeseed (for other scenarios) according to the regional distribution predicted by the models. Climate change impacts associated with production of the marginal crop took crop displacement into account (see Table 4). Only the GTAP model provided GHG emission factors for regional LUC (Table S1, Electronic Supplementary Material), but we applied them for both GTAP and LEITAP. Table 5 summarises worldwide conversion between land use types (e.g. grassland to forest, forest to cropland and grassland to cropland) due to the increase in crop demand and C release/sequestration associated with it, which was predicted by the models and applied to our case studies.

2.4.4 Choice of data used

We assumed that the conversion from an MS to a G farm does not change consumption of inputs such as electricity, fuel, fertilisers, minerals and purchased wheat and will not affect market demand for these inputs; thus, we used average data for them. In contrast, conversion decreases soybean meal consumption by 20.3 t (see Table 1). While the MS farm used meal from "average" soybeans produced in Brazil, most of which are associated with deforestation (Prudêncio da Silva et al. 2010), we assumed that soybean meal bought by the G farm was imported from a region without deforestation (i.e. southern Brazil). We assume that the reduced demand for soybean meal due to farm conversion allows farms to procure soybean meal not associated with deforestation. A summary of sources of data and/or results taken from other studies which were used in our study and their degree of uncertainty are presented in Table S2 (Electronic Supplementary Material).

Table 4 Worldwide climate change impact of increased marginal crop production demand according to the two economic models applied

	Paddy rice	Wheat	Coarse grains[a]	Oilseeds	Sugar crops[b]	Other crops	Marginal crop[c]
Increase in demand for wheat/GTAP							
Area (ha)	−0.03	1.11	−0.33	0.01	0	0.04	0.79
Climate change (t CO_2/ha)[d]	10.14	2.17	2.75	0.50[e]	1.82	0.00	1.58
Increase in demand for rapeseed/GTAP							
Area (ha)	−0.02	−0.05	−0.02	0.47	0	−0.05	0.33
Climate change (t CO_2/ha)[d]	10.14	2.17	2.75	0.95[f]	1.82	0	0.20
Increase in demand for wheat/LEITAP							
Area (ha)	0	1.13	−0.32	−0.16	0.07	0.01	0.73
Climate change (t CO_2/ha)[d]	10.14	2.17	2.75	0.96[f]	1.82	0.00	2.19
Increase in demand for rapeseed/LEITAP							
Area (ha)	0	−0.03	−0.35	2.34	−0.02	0	1.93
Climate change (t CO_2/ha)[d]	10.14	2.17	2.75	0.91[g]	1.82	0.00	0.55

[a] Coarse grain: assumed to consist of a 5:1 ratio of maize and barley, based on 2003–2007 worldwide production (FAOSTAT 2012)

[b] Sugar crops: assumed to consist of a 6:1 ratio of sugar cane and sugar beet, based on 2003–2007 worldwide production (FAOSTAT 2012)

[c] Marginal crop: assumed as the sum of all precedent crops

[d] From Nemecek et al. (2011)

[e] Oilseeds: assumed to consist mainly of soybean, according to model predictions of regional distribution

[f] Oilseeds: assumed to consist mainly of a 1:2 ratio of soybean and rapeseed, according to model predictions of regional distribution

[g] Oilseeds: assumed to consist mainly of a 1:1.5 ratio of soybean and rapeseed, according to model predictions of regional distribution

2.5 Life cycle impact assessment

The environmental impacts of the entire MS farm and its milk, meat and cash crop production were as presented in Nguyen et al. (2013). The impacts of surplus animals for the G farm (relative to MS farm) and of sold animals (for both farms) were determined with system expansion, in which impacts of dairy cattle were assumed to be equal those of suckler beef cattle estimated by Nguyen et al. (2012). The environmental consequences of farm conversion were attributed to the milk, as it drove the decision to convert. The impacts of wheat and rapeseed produced outside the G farm have two components: (1) average worldwide climate change impacts (expressed per hectare) according to Nemecek et al. (2011) and (2) LUC and associated GHG emissions as calculated using GTAP and LEITAP; total impacts are higher than those of wheat and rapeseed produced on the MS farm. Differences between impacts of wheat and rapeseed produced outside the G farm vs. those of wheat and rapeseed produced on the MS farm were

Table 5 Land use change (LUC) emissions (over a 30-year period) due to a gain of 1 ha of cropland and resulting conversion of different land use types, according to the two economic models applied

	Loss of forest (ha)	Emissions from forest loss (t CO_2/year)	Forest gain from grassland (ha)	Sequestration from forest gain (t CO_2/year)	Loss of grassland (ha)	Emissions from loss of grassland (t CO_2/year)	Gain in cropland (ha)	Sequestration from gain in cropland (t CO_2/year)	Emissions per ha of LUC (t CO_2/ha/year)
Applied GTAP in this study									
Increase in demand for wheat	−0.44	−5.7	0.30	2.8	−0.86	−3.2	1.00	0.6	−5.4
Increase in demand for rapeseed	−0.41	−5.0	0.28	2.7	−0.87	−3.1	1.00	0.6	−4.8
Applied LEITAP in this study									
Increase in demand for wheat	−0.89	−12.2	0.03	0.2	−0.14	−0.7	1.00	0.6	−12.1
Increase in demand for rapeseed	−0.88	−12.7	0.00	0.0	−0.12	−0.5	1.00	0.6	−12.6

attributed to G milk. The impact categories considered were climate change including the effects of land use and land use change (CC/LULUC, in kilograms CO_2 equivalent (eq.)) and land occupation (LO, in square metres * year). The impacts CC/LULUC and LO were calculated using the CML2 "baseline" and "all categories" 2001 characterisation methods as implemented in the ecoinvent v2.0 database.

3 Results

The environmental impacts of the entire G farm, including effects of farm conversion, can be expressed as the sum of four components: (a) impacts of production on the G farm itself (including avoided impacts due to avoided production of soybean meal), (b) C sequestration due to on-farm LUC, (c) avoided impacts due to production of more surplus animals than on the MS farm and (d) indirect impacts due to additional wheat and rapeseed produced outside the G farm (Table 6). On-farm LUC (conversion of cropland to grassland and of temporary to permanent grassland) sequesters C, which reduces CC/LULUC of the G farm itself by 15 %. Additional surplus animals from the G farm reduce impacts of the G farm (avoided impacts) by 26 and 15 % for LO and CC/LULUC, respectively. The production of additional wheat and rapeseed outside the G farm induces an increase in its impacts of 40 and 45 % for LO and 29 and 69 % for CC/LULUC with GTAP and LEITAP, respectively. The impacts with GTAP are lower than those with LEITAP for CC/LULUC of wheat (by −18 %) and rapeseed (−81 %) and for LO of rapeseed (−49 %), except for LO of wheat (higher by 65 %). Compared to LEITAP, the use of GTAP for estimating LUC associated with additional wheat and rapeseed yields values for LO and CC/LULUC of the G farm that are 4 and 29 % lower, respectively.

The conversion increases LO and CC/LULUC of the G farm, respectively, by 9 and 7 % with GTAP and by 14 and 51 % with LEITAP (Table 7). As impacts of all conversion consequences are attributed to milk, LO and CC/LULUC of G milk increase, respectively, by 82 and 13 % with GTAP and by 123 and 98 % with LEITAP. Of whole-farm LO and CC/LULUC impacts, milk production contributes, respectively, 19 and 56 % with GTAP and 23 and 69 % with LEITAP for the G farm, compared to 12 and 53 % for the MS farm (see Table 7). Therefore, LO and CC/LULUC per 1 t of grass-based FPCM are, respectively, 0.05 ha*year and 1.12 t CO_2 eq. with GTAP and 0.06 ha*year and 1.95 t CO_2 eq. with LEITAP, whereas per 1 t of maize silage-based FPCM, they are 0.03 ha*year and 0.96 t CO_2 eq., respectively. Contributions of N_2O, CH_4 and CO_2 (expressed as tonnes of CO_2 eq./tonnes of FPCM) to CC/LULUC for different subprocesses of maize silage-based and grass-based milk production varied (Table 8). For grass-based milk production, enteric CH_4 emissions contributed more than N_2O emissions of grassland production. CO_2 emissions related to soybean meal used for maize silage-based milk were much higher than those for grass-based milk (see Table 8), principally due to emissions from deforestation associated with average Brazilian soybean meal in maize silage-based milk production, whereas grass-based milk production used soybean meal not associated with deforestation.

The impacts of wheat and rapeseed produced outside the G farm due to the consequential increase in crop production differ from those produced on the MS farm, respectively, by +39 and +6 % for LO and +239 and +52 % for CC/LULUC with GTAP and by −16 and +108 % for LO and +314 and +687 % for CC/LULUC with LEITAP (Table 9).

4 Discussion

4.1 Methodology of CLCA: from principle to implementation

Application of CLCA modelling requires introducing market mechanisms via affected processes (Zamagni et al. 2012), but identifying the affected processes remains a challenge (Dalgaard et al. 2008; Zamagni et al. 2012). Schmidt (2008) proposed a procedure to identify affected processes in agricultural CLCA, especially of crop production, using a stepwise approach introduced by Weidema et al. (1999). Schmidt (2008) proposed that increased demand for a certain crop can be met by an increase in yield and/or in production area by crop displacement or transformation of non-agricultural land into agricultural land. However, a limitation of this procedure is that crop substitutions were assumed to occur within product types (e.g. one cereal is used instead of another cereal, one oilseed instead of another oilseed) (Zamagni et al. 2012). Currently, products and markets are highly connected on a global scale; thus, increased demand for a product may not only increase its price but also decrease consumption of other products produced elsewhere in the world. Therefore, the use of economic models developed to predict global economic mechanisms is useful and recommended to identify affected processes in CLCA.

Economic models recently have been used to predict changes in land use (Kløverpris et al. 2008, 2010) and GHG emissions due to increased demand for biofuels (Verburg et al. 2009; Edwards et al. 2010). Smyth and Murphy (2011) used a causal–descriptive method to investigate indirect effects of increased biomethane production by anaerobic digestion of grass on the livestock sector in Ireland, whereby cause and effect logic was used to predict system behaviour and define indirect consequences (i.e. affected processes). They assumed that grass biomethane would be produced at the expense of Irish beef production,

Table 6 Effects of the conversion from a maize silage-based dairy farm (MS farm) to a grass-based dairy farm (G farm) on land occupation and climate change impacts of the latter, according to the two economic models applied

	Effects of farm conversion							Total impacts of G farm (after conversion)[a]	
	G farm production itself	C sequestration due to on-farm LUC	Avoided surplus animals	Additional wheat/GTAP	Additional rapeseed/GTAP	Additional wheat/LEITAP	Additional rapeseed/LEITAP	GTAP	LEITAP
Land occupation (ha*year)	59.7		−15.7	14.8	9.0	8.9	17.8	67.9	70.8
Climate change (t CO_2 eq.)	516.3	−77.9	−77.3	103.5	45.0	126.4	233.6	509.6	721.0

[a] The G farm produces the same amounts of outputs as the MS farm

thus decreasing beef exports to the UK, leading the UK to import more meat from other countries. They did not, however, investigate the consequences of increased meat production in other countries. Although the chain of consequences resulting from a change in demand may seem a never-ending story (Weidema et al. 1999), CLCA practitioners should try to consider all consequences up to and including LUC.

In our study, we examined one possible way to meet increased preference for G milk: converting the base of feeding systems on domestic dairy farms from silage maize to grass. Other ways to meet this increase in demand (e.g. importing milk or increasing yields of G milk, see Fig. 1) need to be investigated. We assumed that French consumers would purchase the same quantity of G milk as they did MS milk, regardless of price. However, increasing demand may further increase its price, which may decrease its consumption. As a result, total milk consumption might decrease for a certain time, during which the amount of additional G milk produced would be smaller than the amount of MS milk it replaced.

We also assumed that the MS and G farms would be representative of two major types of French dairy production systems, each of which in reality has some diversity (Devun and Guinot 2012). Nevertheless, the technical parameters for animal performance and farm management used in this study generally correspond to average values for these types of production systems, though for the G farm, grass fertilisation was higher than the average for grass-based farms. Grass on the G farm was highly fertilized with N to maximise yield and thus milk production per hectare. Lower N fertilisation would have reduced GHG impacts but no doubt increased the area of grass necessary on the farm, leading to greater LUC and associated GHG emissions. Moreover, we did not consider the fact that in the future, once many MS farms have converted to G farms, "new" G farmers may find ways to increase animal performance and farm productivity, which would decrease the impacts of the G farm.

Another simplification in our study was the assumption that the additional beef produced by the G farm would replace meat produced by a suckler beef system. In addition, the increase in beef production due to dairy farm conversion could reduce beef price and, consequently, would affect consumption of the other types of meat as well (not only beef from suckler cattle). Kløverpris et al. (2010) used GTAP to predict the effects of increased household wheat consumption (resulting in a higher price) on LULUC. They estimated that due to limited household budgets, increased wheat consumption would be balanced by an equal decrease (in monetary terms) in consumption of other commodities.

Our study, contrary to many others, included the consequences on LULUC impacts. First, the G farm replaces an MS farm, which affects the on-farm cropping pattern and crop management practices and hence on-farm soil C dynamics. Secondly, the G farm requires more land to produce the same quantity of milk as the MS farm. Thus, the area used for cash crop production decreases, which subsequently shifts demand in the market to other sources. These effects were accounted for by using GTAP and LEITAP simulation results as reported by Edwards et al. (2010). Application of the GTAP and LEITAP models seemed justified by the fact that these models are either linear or nearly so, i.e. increases in crop area are roughly proportional to the extra demand for a particular crop (Edwards et al. 2010). Because these models cannot simulate more than one crop at a time, we assumed that the farm conversion consequences on LUC due to the increase in demand of wheat and rapeseed are additive.

4.2 Co-product handling

Once consequences of farm conversion are defined, the difficulty remains of how to attribute the effects of these

Table 7 Impacts for the whole farm and for milk production of a maize silage-based dairy farm (MS farm) and a grass-based dairy farm (G farm) after conversion, and increase in impacts due to conversion expressed as a percentage of those of the MS farm, according to the two economic models applied

	Before farm conversion (MS farm)				After farm conversion (G farm[a])				Increase (%) of impacts due to conversion			
	Whole MS farm	Total milk production MS farm	Total meat production MS farm	Total cash-crop production MS farm	Whole G farm/GTAP	Whole G farm/ LEITAP	Total milk production G farm/GTAP	Total milk production G farm/LEITAP	Whole farm/GTAP	Whole farm/ LEITAP	Milk production/ GTAP	Milk production/ LEITAP
Land occupation (ha*year)	62.0	7.1	29.2	25.7	67.9	70.8	13.0	15.9	9	14	82	123
Climate change (t CO_2 eq.)	476.1	250.8	146.2	79.0	509.6	721.0	284.3	495.8	7	51	13	98

[a] The G farm produces the same amounts of outputs as the MS farm

consequences to several products. Although increased preference for G milk drives farm conversion, one wonders whether G milk should be held responsible for the impacts of subsequent consequences. As dairy production systems produce both milk and beef, some impacts associated with these consequences could be attributed either to all beef or just the additional beef (compared to that from the MS farm) produced by the G farm. By estimating the impacts of G beef as equal to those of suckler beef (using system expansion), some impacts of farm conversion were attributed exclusively to beef. This is because the suckler beef cattle system is also based mainly on grassland (like beef meat from G farm), and its beef has been shown to have higher environmental impacts than dairy beef (when allocation methods were applied for milk and its co-product dairy beef) (Nguyen et al. 2013).

4.3 Effects on LUC

The use of economic models is appropriate for taking into account indirect effects of farm conversion on LUC (Prins et al. 2010). However, the predictions of these models have high variability and uncertainty due to their characteristics, hypotheses and assumptions (Laborde 2011; Marelli et al. 2011). GTAP and LEITAP predictions for wheat and rapeseed clearly reveal this variability, which resulted mainly from the way that change in surface area is calculated per crop per region. LEITAP assumes that the area of crop expansion depends strongly on the average yield of the particular crop whose production increases, whereas GTAP assumes that it depends on the yield of that same crop at the frontier of cultivation, i.e. in the region where LUC occurs. Thus, GTAP includes a factor which estimates the yield at the frontier of crop production, where LUC resulting in marginal increases in agricultural area actually occurs (Edwards et al. 2010).

The models also differ in the way that additional production is shifted from countries with high yields to less developed countries with lower yields (Edwards et al. 2010). Other parameters differ, such as the factor increasing yield with price and the reduction factor due to by-product use or food consumption (Edwards et al. 2010; Prins et al. 2010). In our study, the same gross demand for feedstock yielded large differences in predicted LUC and its emissions in the two models, despite not using the by-product reduction factor and using the GTAP emission factor for LUC for both models. Compared to GTAP, LEITAP predicted increases in LUC area and emissions up to two and five times larger, respectively (see Tables 3 and 8). In LEITAP, nearly 90 % of LUC is converted from forest and the rest from grassland into cropland, whereas in GTAP, nearly 90 % LUC is converted from grassland into cropland. In addition,

Table 8 Contribution of N_2O, CH_4 and CO_2 to climate change impact (in tonnes of CO_2 eq./tonnes of milk) of milk produced from a maize silage-based dairy farm (before farm conversion) and from a grass-based dairy farm (after farm conversion), including effects of farm conversion on land use change, according to the two economic models applied

	Maize silage-based milk				Grass-based milk			
	N_2O	CH_4	CO_2	Total	N_2O	CH_4	CO_2	Total
Enteric fermentation	0.00	0.41	0.00	0.41	0.00	0.59	0.00	0.59
Manure management	−0.04	0.14	0.00	0.10	−0.04	0.06	0.00	0.02
Grassland production	0.11	0.00	0.04	0.15	0.50	0.01	0.21	0.72
Soybean meal production	0.01	0.00	0.16	0.17	0.00	0.00	0.02	0.02
Other feed production	0.10	0.00	0.04	0.14	−0.01	0.00	0.00	0.00
Farm management	0.00	0.00	0.02	0.02	0.00	0.00	0.03	0.03
C sequestration due to on-farm LUC					0.00	0.00	−0.31	−0.31
Avoided surplus animals					−0.15	−0.15	0.00	−0.30
Additional wheat/GTAP[a]								0.29
Additional rapeseed/GTAP[a]								0.06
Additional wheat/LEITAP[a]								0.38
Additional rapeseed/LEITAP[a]								0.80
Total				0.96				1.12/GTAP 1.95/LEITAP

[a] Details on N_2O, CH_4 and CO_2 are not available for results obtained from economic models

in GTAP, nearly 68 % of the total forest loss is converted to grassland (only up to 3 % in LEITAP).

4.4 Uncertainty

In CLCA modelling, the high degree of uncertainty and wide range of possible results depend on choices regarding (1) system enlargement (and thus on the affected processes taken into account), (2) the indirect effects included and (3) the hypotheses, assumptions and scenarios considered (Zamagni et al. 2012). Uncertainty is also a critical issue in estimating the effects of LUC (Edwards et al. 2010; Prins et al. 2010; Laborde 2011; Marelli et al. 2011). Apart from model characteristics and assumptions used to predict LUC, uncertainty also results from a crop's estimated increase in yield with price and future trade (Prins et al. 2010) and assumptions about how its production will shift among regions and on what type of land (forest, grassland, cropland) it will be produced. It is important to interpret LUC results with caution, because the models predicting them are complex and, as previously mentioned, often have different parameter values, leading to a high degree of uncertainty in their predictions. Last but not least, estimation of CO_2 emissions due to crop expansion on forest or grassland is also highly uncertain.

In our study, assessment of the impacts of the on-farm production system is probably less uncertain than the estimated consequences outside the farm due its conversion. First, as described in Nguyen et al. (2013), enteric CH_4 was estimated with the Tier-3 method used in the French Inventory of Greenhouse Gases (Vermorel et al. 2008), as recommended by Intergovernmental Panel on Climate Change (IPCC) (2006) to improve the accuracy of emission estimates. Our data on DM intake, milk production, herd management and farming practices were taken from a systems experiment (for G farm) (Delaby et al. 2009) and a farm network followed by the French Livestock Institute (for MS farm) (Pavie et al. 2010), which can be assumed to have low

Table 9 Environmental impacts of wheat and rapeseed produced on maize silage-based dairy farm (MS farm) or produced outside of grass-based dairy farm (G farm) due to the farm conversion according to GTAP and LEITAP models

	Wheat on MS farm[a]	Rapeseed on MS farm[a]	Wheat outside G farm/GTAP	Rapeseed outside G farm/GTAP	Wheat outside G farm/LEITAP	Rapeseed outside G farm/LEITAP
Land occupation (ha*year/t)	0.16	0.32	0.22	0.33	0.14	0.66
Climate change (t CO_2 eq./t)	0.46	1.10	1.57	1.67	1.91	8.65

[a] Results from Nguyen et al. (2013)

uncertainty. Our estimates of N_2O emissions are based on IPCC Tier-2 (IPCC 2006) emission factors, which have relatively high uncertainty.

Regarding on-farm soil C dynamics, for sensibility analysis, we also simulated a 100-year period after farm conversion with RothC, in addition to the 30-year period. During the 100-year period, predicted on-farm soil C sequestration was 45.7 t CO_2/year, which was 43 % lower than the 79.7 t CO_2/year during the 30-year period, indicating that C will continue to be sequestered after the first 30 years after conversion, but at a lower rate. If considering a 100-year period, total climate change impact of the G farm (after conversion) would be 7 and 5 % higher than its impact estimated with a 30-year period for GTAP and LEITAP, respectively (results not shown). So, the time frame for estimating soil C dynamics is an important factor contributing to uncertainty.

Ultimately, we investigated only one of the many potential cause and effect pathways of farm conversion, which limits the study's ability to quantify uncertainty, despite using two models to estimate LUC consequences. Scenario analysis of other potential consequences of this type of farm conversion would enrich further studies.

4.5 Consequences of increased preference for grass-based milk

This study has illustrated how an increase in preference for G milk could be met and explored its potential environmental consequences. Without considering the consequences of reduced on-farm production of cash crops which occur outside the G farm boundary (i.e. indirect consequences), climate change and land use impacts of the G farm were substantially lower than those of the MS farm (by 24 and 29 %, respectively). Including indirect consequences necessary to compensate for decreased outputs from the G farm greatly increased impacts of the G farm, in function of how indirect effects were estimated. Therefore, for such a conversion, it would be misleading to only look at what happens at the on-farm level, because of the major indirect effects outside the farm.

In our study, C sequestration resulting from on-farm LUC and CO_2 emissions due to LUC for additional crops were amortised over 30 years. As C sinks/sources resulting from sequestration/emission activities in soil or biomass are not permanent (e.g. Smith 2005), we assumed that soil C reaches a new equilibrium after 30 years and remains stable. So, the results presented in this paper concern the 30-year period after conversion. After this period, climate change impact of the G farm (including indirect consequences resulting from cash crop production outside the G farm) would be slightly lower (less than 2 % with GTAP and 3 % with LEITAP) than that of the MS farm (results not shown). In contrast, direct and indirect land occupation of the G farm remains higher and, therefore, the consequences in terms of biodiversity loss due to forest and pasture conversion into cropland remain.

5 Conclusions

Contrary to an ALCA approach, the CLCA approach allows assessing the consequences of a change in the life cycle on the processes beyond the system boundary, in particular on LUC. The integration of global economic models in CLCA modelling is necessary to identify and assess the processes affected by a change in the life cycle. This study demonstrated how environmental consequences of increased preference for grass-based milk can be assessed using the CLCA approach. Although this study investigated only one way to meet this increased preference, it indicates that conversion of a maize silage-based to a grass-based dairy system would probably have consequences on LUC outside the farm and that it is important to consider them. However, scenario analysis needs to be performed in future studies to explore other possible consequences. Finally, the approach applied in this study needs to be further developed to identify advantages and disadvantages of using grassland in ruminant feeding systems worldwide.

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